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Generation and use of standardised load spectra and load–time histories

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Abstract

Generally the basic fatigue behaviour of materials and structures is determined adopting constant amplitude loading resulting in various characteristic quantities and relationships such as S–N curves, cyclic stress–strain curves, fatigue crack growth rates, threshold values, etc. While constant amplitude loading is fully described by quite a few parameters (maximum/minimum or range/mean and number of load cycles), most structures experience in-service loading environments with variable amplitudes and mean loads. It is well established that fatigue response may be very sensitive to the specifics of the loading encountered. Therefore, tests with realistic load sequences are often required in order to assess any susceptibility to that kind of phenomenon and to demonstrate the in-service integrity for given materials and structures.

For this purpose standardised load–time histories have been developed for 30 years since it has been recognised that the use of standardised load–time histories provides a series of advantages—both for studies of a more generic nature and practical applications. The present paper deals with this topic. Starting from an overview on standardised load–time histories available at present, it details the principles applied for collection and analysis of appropriate load data, assessment of operating profiles and generation of the respective load spectra and sequences. The principles may also serve as guidelines for those cases where new load spectra and load–time histories have to be created, for example, for a given design problem. This as well as some other types of application are reported in a final section based on information collected from the literature.

Keywords: Variable amplitude loading; Load sequences; Fatigue

1. Introduction

The topic of cumulative damage has been studied for decades recognising the nature of variable amplitude load environments most structures experience in service. It is well-known that data and models that characterise the fatigue behaviour of materials and structures under base-line constant amplitude loading may not be appropriate or sufficient to adequately assess their fatigue performance under irregular variable amplitude loading. Basic research is conducted under use of simplified load sequences such as single overload or underload or block loading with alternate mean loads. Phenomena like crack growth retardation or acceleration are described making reference to base-line constant amplitude data. It is generally agreed, however, that real life load spectra also need to be applied in order to get a realistic picture of the relevance and significance of the mechanisms involved.

Standardised load sequences or load–time histories (SLH's[1]) presently available provide an appropriate selection of load sequences for that purpose, but they can also advantageously be used for other tasks.

In the present paper, an overview on and a summarising description of standardised load–time histories is given followed by a discussion of principles, approaches and solutions relevant for the analysis of load data and

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[1] The acronym SLH is generally used for 'standardised load–time histories' as well as for 'standardised load sequences', including 'load spectra'. More specifically, it is distinguished between 'load–time history' for processes with actual time information (e.g. multiaxial, real-time processes) and 'load sequence' as a succession of loading events without explicit time information (e.g. load turning points, typically uniaxial applications).

generation of SLH's. Finally examples from the literature are reported where SLH's were applied for a variety of tasks and purposes.

2. Existing standardised load time-histories

In this section, the SLH's developed mainly in Europe, Table 1, and some approaches taken in the US are presented. The SLH's are briefly characterised and some numbers are compiled that enable a first assessment of typical features of the respective load sequence. Further details are given in some overview papers [1–4] and in the respective original papers and reports.

2.1. Overview

Table 1 lists the SLH's generated by European working groups over the last nearly 30 years. With the need for optimum light-weight design, originally the aircraft industry was the main driver for these efforts. Two of the most well-known SLH's are the TWIST and FALSTAFF sequences for transport and fighter aircraft, respectively, which have been and are still being applied for numerous studies on materials, joints and other structural elements. HELIX/FELIX and the two TURBISTAN sequences are further examples from the aerospace field. Because of the relatively high number of cycles of the TWIST and HELIX/FELIX sequences, shortened versions of these SLH's have been also devised as has been done later with the WISPER and other sequences.

As Table 1 indicates, starting in the mid 1980s, SLH's for non-aerospace applications have been developed covering areas such as wind turbines, offshore platforms or steel mill drives. For automotive applications, the CARLOS series of SLH's have been presented including the very recent load sequence for car trailer couplings, CARLOS-TC.

In the US, activities were mainly centred on the derivation of test load sequences to be used for evaluation and development of fatigue life prediction methodology. Bodies like the SAE Fatigue and Evaluation Committee took a pragmatic approach by selecting test load sequences from existing strain measurements, which were felt to be typical for the ground vehicle industry. The early quite short sequences published in 1977, Table 2, were followed later by biaxial sequences that again were based on a set of measurements made available from different sources, but were more realistic with regard to spectrum length and distribution of small and large cycles. Similarly in the US aircraft community a variety of load sequences have been generated and distributed without the formal framework of European SLH's, for example sequences typical for fighters (F-16) or transports (C-5) with different mission-dependent load cycle distributions. These load sequences are frequently used for validation of numerical fatigue life prediction concepts and software packages [5,6].

2.2. Discussion of spectrum parameter details

Spectrum loading tests have to be performed when the fatigue behaviour cannot be assessed based on simple constant amplitude data with the required level of confidence [67]. This is particularly true when the load spectra involved clearly 'differ' from constant amplitude loading in terms of amplitude and mean stress fluctuations and/or when multi-directional (multiaxial) loading has to be considered. Data compiled in Table 1 help to characterise some of the features of the respective SLH's in this respect. This information may be relevant to the user who looks for load histories typical for specific applications. But furthermore, it provides an input for those who are interested in general research on cumulative damage effects, since it may be necessary to apply several load sequences with rather differing features in order to elucidate the validity and limitations of models and hypotheses. Thus, somebody might use TWIST not because it represents the loading of the lower wing root of transport aircraft, but because it contains frequent underloads.

Table 1 specifies the type of load sequences in a condensed manner also indicating whether mean stress fluctuations are included. The majority of the earlier SLH's define a sequence of normalised peaks and troughs of a single load component without any time or phase information. Exceptions are ENSTAFF where six different temperature levels are associated with the FALSTAFF load reversals and Hot TURBISTAN where additional dwell times are introduced at appropriate load levels, Fig. 1, in order to allow for the interaction of mechanical and environmental effects, for example the oxygen-induced embrittlement of nickel base superalloys. After the introduction of the three uniaxial CARLOS sequences for wheel suspension parts, the aspect of multi-directional loading was reflected by the subsequent CARLOS multi SLH's. Multi-directional loading is found for many real-life applications and requires consideration of more than one load component and their respective phase relationships.

Generally a SLH is defined as a spectrum that does not cover the total expected in-service spectrum, but only a representative fraction (return period). Thus, this spectrum is thought to be repeated in a test or a numerical simulation until final failure or the anticipated usage would be safely covered. If the respective design lives are taken into account, for example the number of, say, 50 years for offshore installations or the number of flights for commercial (>60–120,000 flights) or military aircraft (>8000–16,000 flights), the number of repetitions of the standardised spectra can be estimated for a test at realistic stress levels. This may be interesting for an assessment of the necessary effort in terms of testing time and cost, but it is also relevant with regard to a realistic overall spectrum

Table 1
European standardised load sequences and load–time histories

Name	Purpose	Structural detail	Description of load history	Load channels[a]	Block size (cycles)[b]	Equiv. usage	SSF[c]	No. of load lev.	Year/Ref.[d]
TWIST	Transport aircraft wing root	Wing root bending moment	Const. positive mean stress for gust loads, ground-air-ground cycles (GAG) = underloads	1	402,000	4000 flights	3.09	20	1973 [58]
GAUSSIAN	General purpose random sequence	Narrow-band to wide-band random (3 levels of irregularity, I)	$I=0.99\rightarrow$ no mean stress fluctuation,	1	1.0×10^6	–	2.32	20	1974 [59]
			$I=0.70\rightarrow$ minor mean stress fluct.		1.4×10^6		2.59		
			$I=0.33\rightarrow$ considerable mean str. fluct.		3.3×10^6		3.24		
FALSTAFF	Fighter aircraft	Wing root	Manoeuvre dominated spectrum, moderate fluct. of mean stress, GAG	1	18,000	200 flights	2.54	32	1975 [60]
Mini TWIST	Shortened version of TWIST		Omission of low gust load cycles	1	62,000	4000 flights	2.26	20	1979 [61]
HELIX, FELIX	Helicopters, hinged and fixed rotors	Rotor blade bending	Blocks of cycles with different amplitude and mean stress levels	1	2.3×10^6	140 flights	1.70, 2.62	H: 31, F: 33	1984 [62]
					2.1×10^6				
HELIX/32, FELIX/28	Shortened versions	As above		1	2.9×10^5	140 flights	1.54		1984 [62]
					3.2×10^5		1.82		
Cold TURBISTAN	Tactical aircraft engine discs	Bore	Min–max cycles + high mean stress cycles, no compressive loads	1	7700	100 flights	1.65	50	1985 [63]
					3200		1.31		
					1000		0.80		
ENSTAFF	FALSTAFF + temperature	Wing root (CFRP)	As FALSTAFF + six temperature levels	2	18,000	200 flights	2.54	32	1987 [64]
WISPER/WISPERX	Wind turbines (X, shortened version)	Blade out-of-plane bending	Blocks of gust loading with const. mean stress, diff. mean stress levels	1	132,700/ 12,800	2 months	2.96	64	1988 [24]
							2.35		
Hot TURBISTAN	Tactical aircraft engine discs	Rim	Similar to Cold TURBISTAN, dwell periods (in total 8 h per 100 flights) at different mean stress levels	2	8200	100 flights	1.80	50	1989 [65]
Wash I	Offshore structures	Structural members of oil platforms	Composed of narrow band loading with six sea states of varying intensity	1	5×10^5	1 year	3.87	14	1989 [12, 13]
WAWESTA	Steel mill drive	Drive train components	Sequence of 10,000 milling runs	1	28,200	1 month	1.97	23	1990 [66]

(*continued on next page*)

CARLOS	Car loading standard (3 uniaxial sequences)	Vertical, lateral, longitud. forces on front suspension parts	Random with occasional fluctuations of mean stress, mixture of five road types, $R=-0.18$ (ve), -0.64 (la), -1.6 (lo)	1	ve: 136,000 la: 95,200 lo: 84,000	40,000 km	2.66 2.46 2.70	≤64	1990 [10]
CARLOS multi	Car loading standard (multiaxial)	Four-channel load components for front suspension parts	Time histories, sample frequency 0.005 s, correlation functions between load components based on guide functions	4	Similar to CARLOS uniaxial	40,000 km	Similar to CARL. uniaxial	–	1994 [23]
CARLOS PTM	Car power train (manual shift)	Power train comp. e. g. clutch, gearwheels, shafts, bearings, universal joints	Load-time histories and load sequences of torques and speeds, separated for five gear positions test variants optimised for different assembly groups	2	Depends on transm. in-/output gear position	6000 km	2.49 (Transm input) gear pos 1–5,	–	1997 [11]
CARLOS PTA	Car power train (automatic transmissions)	Power train components, similar to PTM	Similar to CARLOS PTM	2	Depends on transm. in-/output, gear pos.	6000 km	1.92 (Transm output) g.p.1–5	–	2002 [21]
CARLOS TC	Car trailer coupling, passenger vehicles	Trailer coupling devices and vehicle supporting structure	Load-time histories (longitud., lateral, vertical), optimised for test time and test facility limits	3	3 short blocks, repetition rule	Total life verification	lo: 3.78 la: 3.05 ve: 3.05	–	2003

[a] No. of load components or additional variables (time, temperature, etc.).
[b] Approx.
[c] Spectrum shape factor (see Section 2.2).
[d] Partly the references do not cite the original report(s), but those available to the public.

Table 2
Standardised load–time histories from the US

Name	Purpose	Load comp.	Block size[a]	Year/ Ref.
Transmission	Tractor transmission (torque)		854	1977 [7]
Suspension	Vehicle suspension (bending moment)		1253	1977 [7]
Bracket	Vehicle mounting bracket (rough road)		2968	1977 [7]
Agricult. tractor	Drive axle, several typical operations	Bending	3.1×10^5	1989 [8]
		Torsion	3.1×10^5	
Log skidder	Drive axle, operation in forests	Bending	31,800	1989 [8]
		Torsion	18,700	

[a] Cycles.

shape where the (calculated) fatigue damage is properly distributed over large, medium and small cycles. A small block size (return period) and a large number of repetitions of the spectrum may create a severely truncated overall spectrum where much of the damage would be contributed by the largest cycles. If not dictated by the particular structural application, the cumulative frequency of the maximum load level is recommended to lie within the range of about 10–200.

Table 1 specifies an additional number, the 'spectrum shape factor', SSF, that represents the distance (factor, life ratio) between an (arbitrary) Wöhler S–N curve and the associated spectrum fatigue life curve (in Germany sometimes referred to as Gassner curve in honour of Ernst Gassner), Fig. 2. This factor is calculated using the Miner damage rule (without endurance limit)

$$\mathrm{SSF} = \log\left[\sum n_i \Big/ \sum n_i \cdot \left(S_{a,i}/S_{a,\max}\right)^k\right] \quad (1)$$

It solely depends on the shape of the spectrum under consideration and the slope, k, of the Wöhler curve where $k>1$. For metals the slope k normally ranges between 3 for structures with sharp notches or cracks and $k=12$–15 for smooth polished specimens. For the present purpose an intermediate value of $k=5$ has been selected that would represent average quality components. $S_{a,i}$ and n_i are, respectively, the load amplitudes and associated number of cycles of the rainflow-counted spectrum and $S_{a,\max}$ is the maximum load amplitude of the spectrum.

For an interpretation of the SSF variable, typified amplitude spectra according to Gassner et al. are considered, Fig. 3, that may be described by

$$\ln H_i = \left[1-(S_{a,i}/S_{a,\max})^{\nu}\right]\cdot \ln H_0 \quad (2)$$

where

H_i cumulative frequency of load cycles for load level $S_{a,i}$;
H_0 block size (number of rainflow cycles);
ν shape exponent.

With decreasing values of ν, the shapes of the amplitude spectra become more and more hollow. Table 3 details some numbers of ν and associated SSF for the spectra shown in Fig. 3 (block size $H_0=10^6$).

Since the amplitude spectra of some of the SLH's cannot be approximated by the typified load spectra of Fig. 3, the variable SSF has been devised to characterise the respective *amplitude* spectrum shapes and their relative 'distance' to constant amplitude loading. From Eq. (1) and Table 3, it is evident that SSF = 0 means constant amplitude loading and SSF < 1 are valid for spectra with many large and few small cycles. For hollow spectra with only a few large cycles and many small cycles, SSF > 3 may be valid which means the respective Gassner curve is shifted right of the Wöhler curve by more than three decades. It is general experience that the larger this SSF value, the more one has to expect non-linear cumulative damage phenomena, i.e. problems with (linear) damage models and calculations.

It should be noted, however, that *mean stress* effects—if present—are *not* covered by the SSF variable. Varying mean stresses are known to equally deteriorate the accuracy of linear damage calculations even if mean stress effects are taken into account by a Goodman correction or similar approaches. Therefore, the SSF variable has to be interpreted with caution for those cases.

A second note refers to the influence of the block size, H_0, and/or omission on the variable SSF. Generally the fatigue life under spectrum loading is discussed in terms of equivalent usage, e.g. number of flights or kilometres, etc. The SSF variable is derived on a number-of-cycles basis,

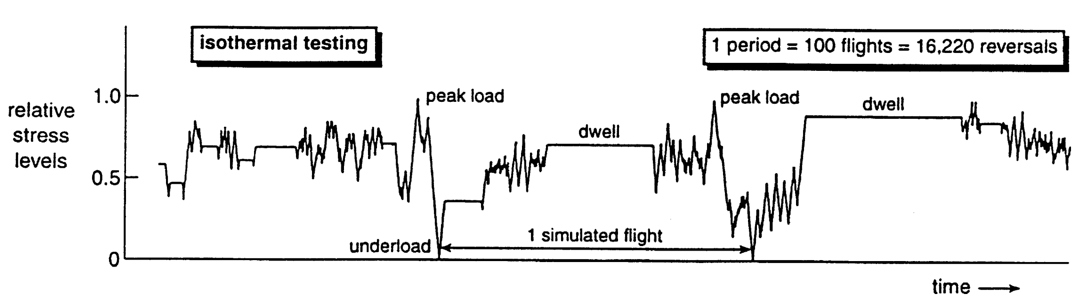

Fig. 1. Segments of Hot TURBISTAN, load reversals plus dwell times.

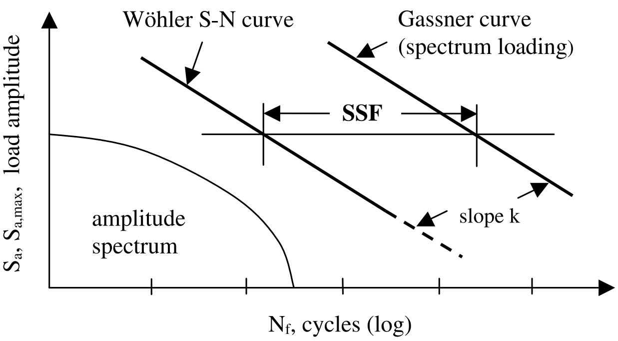

Fig. 2. Wöhler and Gassner S–N curves and the factor SSF.

which means it will be influenced by omission. Whereas omission of small non-damaging cycles should not affect the resulting fatigue life in terms of equivalent usage, it will change the spectrum shape and thus also the SSF values as can be seen for TWIST, HELIX/FELIX and WISPER and their respective shortened derivatives, Table 1.

3. Generation of load spectra and load–time histories

3.1. General considerations

It is generally agreed that the structural load variations should be characterised in the *time domain* since in most cases the range (or amplitude) of a load, stress or strain cycle plus its respective max or mean value can be considered as fatigue-relevant. Furthermore, the sequence or mixture of load cycles of different ranges and means must not be neglected. Analyses in the *frequency domain* give insight into the frequency content of a load signal which is particularly instructive for flexible structures, but do not deliver the above-mentioned values.

Many structural loading environments can be described as sequences of different modes [2] which may be a particular flight, driving a car on certain road types, a sea state of a given severity, etc. These modes of operation contain load cycles of different, but typical magnitudes and frequencies. Often distinct patterns of grouped load cycles can be distinguished, called a loading event or element, such as braking or cornering of a car, different flight phases or manoeuvres of an aircraft. The occurrence of modes and loading events has to be defined in terms of frequency, severity and mixture/sequence, which in summary establish the so called operating profile, Fig. 4.

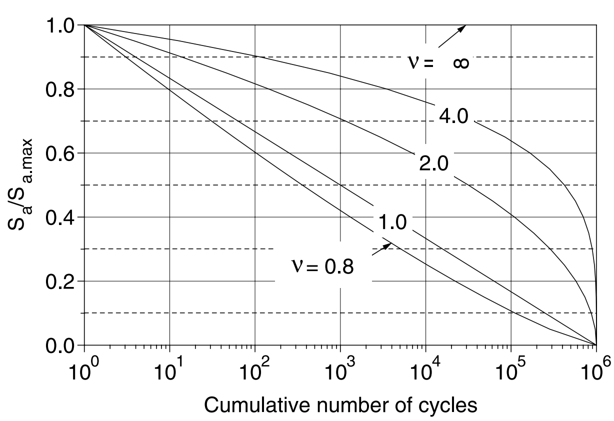

Fig. 3. Typified load amplitude spectra.

As a basic input to SLH generation, statistically adequate samples of load measurements under operational conditions have to be available for every loading event. By means of data evaluation and processing the measured loading samples are prepared for compilation according to the operating profile. Thus, the overall load spectra will be defined, but for definition of the final load sequences and/or load time histories further steps have to be taken that are addressed in Section 3.5.

Experience shows that the development of a SLH should be a co-operative effort of several contributors in order to create a statistically significant data base and to consider the various aspects and requirements effectively. The principles adopted and the range of application should be clearly documented and published.

3.2. Operating profiles

The operating profile describes the service conditions for the total or a representative fraction of the operating period. A difficulty is the fact that for different sections of, say, an aircraft, different operating profiles may have to be composed. That becomes quite clear by the comparison of e.g. airplane wings and landing gears: the wings are loaded by the take-off and landing load (ground-air-ground) cycles and the superimposed flight gust loads. The nose landing gears see, on the other hand, the push back, towing, taxiing, take off, landing impact, braking and landing roll operations. In the automotive area, a similar situation is found e.g. for wheel suspension, drive train and body/trailer-coupling components; the operating profiles of the respective SLH's diverge correspondingly [10–11].

Table 3
Spectrum shape parameters ν and SSF for typified amplitude spectra

Spectrum	ν	SSF	Description
1	∞	0	Constant amplitude loading
2	4	1.46	$\nu > 2$ typical for bridge and crane structures
3	2	2.45	Stationary Gaussian random process
4	1	3.77	Typical for road roughness induced loads
5	0.8	4.21	$\nu \leq 1$ typical for wind gusts, wave actions, etc.

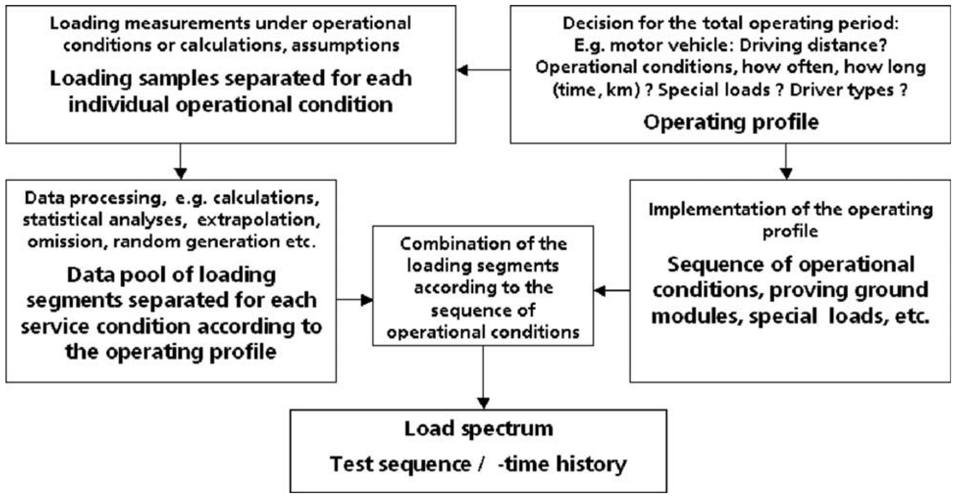

Fig. 4. General (simplified) approach for the generation of SLH's (example: passenger vehicle).

The approaches for determination of operating profiles depend on the type of structural application concerned. The use of airplanes, helicopters, offshore structures, wind energy plants, etc. can, as a rule, be predicted and verified quite well. Operating profiles can therefore be based on reliable data, e.g. mission profiles (aircraft), meteorological long-time wind (wind energy plants) or sea state observations (offshore platforms), e.g. [12,13]. On the other hand, the use of passenger cars and the driving behaviour may not predicted to the same degree of reliability, because it has to cover a great variety of road conditions (e.g. city, mountain, highway, off-road) and driving modes (conservative, sporty, up to special events like misuse, accidental scenario) which results in large scatter levels. Therefore, the philosophies of car manufacturers differ considerably with regard to operating profile determination generally laid down within particular driving rules for special proving ground modules or public roads. Great efforts have been and are being taken to update this data base by investigations on real customer in-service usage, e.g. [14].

3.3. Analysis of operational loads

Statistically adequate samples of operational loads have to be available for every load case. These samples are usually acquired by in-service measurements, but they may also be supported by calculations or simple assumptions. Data processing aims at the preparation of the measured samples to be used as a basis for the generation of test load sequences compiled according to the operating profile, comp. Fig. 4. Table 4 summarises the procedures that may be applied for analysis purposes.

Today, the two-parametric *rainflow counting* has the greatest significance for time domain fatigue analyses. The result is the rainflow matrix (with residuum) that contains the number, amplitudes and mean values of load cycles that can be traced back to closed stress–strain hysteresis loops of a representative material element. These load cycles are considered to be the basic damaging elements of a load sequence. Rainflow

Table 4
Compilation of relevant procedures for load analysis

Procedures to analyse operational loads		Test conditions	
		Stiff component	Dynamic response
Loading conditions	Uniaxial loading	Rainflow counting (level crossings—l.c., range pairs—r.p.)	Additional Fourier analysis (e.g. power spectral density)
	Rotating loading	Rainflow counting (l.c., r.p.) Dwell time and/or revolution-at-level counting	Additional Fourier analysis (e.g. power spectral density)
	Loading under environmental impact	Rainflow counting (l.c., r.p.) Consideration of dwell time (environmental impact)	Additional Fourier analysis (e.g. power spectral density)
	Multiaxal loading	Rainflow counting (l.c., r.p.) Correlation analyses, e.g. joint density (multiaxial dwell time) counting	Additional Fourier analysis (e.g. auto-, cross spectra, coherence functions, transfer matrices)

matrices serve for damage calculations and/or for the reconstruction of uniaxial random load sequences partly under consideration of omission of small, non-damaging load cycles (see below). However, the visual comparison and evaluation of rainflow matrices is difficult or hardly possible—for this purpose often the *level crossing* and *range pair* distributions (rainflow-ranges) are extracted from the rainflow-matrix (or directly counted). Moreover, these one-parametric distributions are especially significant for the present topic because the earlier standardised load spectra have been described by level crossing and/or range pair counting.

Using the counting procedures mentioned so far, the time, frequency and phase information of the load signals are lost which may be, however, relevant for rotating loading, the consideration of environmental impact or multiaxial loading. Some information will be given in Section 3.5, but for more details the reader should refer to the respective literature, e.g. [15–18] for counting methods and e.g. [19,20] for Fourier analyses.

3.4. Determination of load spectra by extrapolation

The load cycle distributions derived from sample measurements have to be extrapolated according to the requirements of the operating profile. The simplest way is the plain repetition (factor for the cumulative frequency of every loading element) without extrapolation of the maximum load levels. This may be sufficient when the maximum loads are well defined and already covered by the measured loading elements available (e.g. vehicle applications with extreme values measurements in proving grounds), Fig. 5.

If only segments of a random load sequence are available, generally extrapolation up to physical limits will be necessary. A simple, but well-suited approach for continuous loading environments would rely on extrapolation based on an approximation of the respective sample load spectra by exponential distributions, Eq. (2) [25]. However, for loading environments with discontinuous single loading events the above mentioned method may fail. In this case the distribution of extreme values originating from consistent physical causes has to be considered. According to experience, the extreme value distributions can be well approximated by Weibull- or log-normal distributions. An additional advantage is the possibility to determine certain probabilities for extrapolated extreme values and the confidence level of the approximation [25,53].

Direct extrapolation of rainflow matrices as proposed in [54,55] is, of course, possible in the case of the simple multiplication of numbers of cycles (under consideration of residua) and may be applicable also for the amplitude extrapolation in case of large samples of continuous processes. However, in general cases including small sample sizes or discontinuous loading events, the extrapolation of rainflow matrices has to be critically reviewed.

In principle, the methods mentioned are applicable for uniaxial loading and one-parametric distributions. However, in the framework of the so called Simultaneous procedure [22], where basic elements are not load cycles, but short (multiaxial) load segments, they can be applied for the extrapolation of multiaxial processes including two-parametric distributions (rainflow, joint density distributions), too.

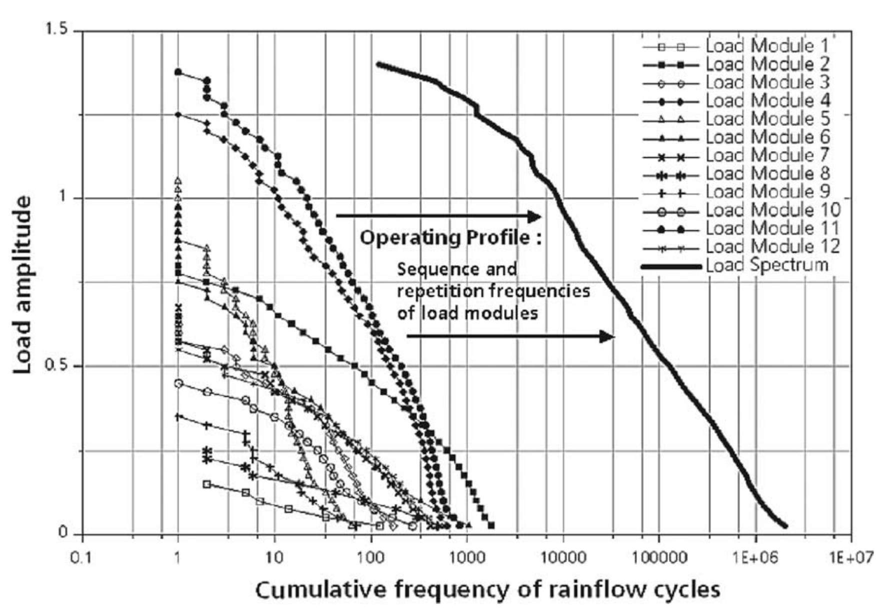

Fig. 5. Compilation of a load spectrum by simple repetition of loading segments according to the associated operating profile.

Table 5
Compilation of procedures to synthesise test loads

Procedures to synthesise test loads		Test conditions	
		Stiff component	
Loading conditions	Uniaxial loading	Combination of loading segments (reduced to turning points) Random rainflow reconstruction Simplified (blocked) test programs based on level crossings and/or range pair distributions	Combination of real-time loading segments Generation of random processes with defined power spectral densities (possibly additional effective-value distributions)
	Rotating loading	Combination of loading segments Random rainflow reconstruction (or simplified test programs), taking into account the dwell time and/or revolution-at-level distributions Simplification: e.g. block-wise constant speed	Combination of real-time loading segments according to the desired load distributions and acceptable test time
	Loading under environmental impact	Combination of loading segments Random rainflow reconstruction (or simplified test programs) under consideration of dwell time	Combination of real-time loading segments according to the desired load distributions and acceptable test time
	Multiaxal loading	Combination of measured loading segments Guide function procedure, combined with calculation of correlated variables Calculation of optimised loading segments (simultaneous procedure)	combination of real-time loading segments according to the desired load distributions and acceptable test time

3.5. Generation of load sequences and load time-histories for fatigue tests

For the synthesis of test load sequences and load time-histories, approaches compiled in Table 5 will be applied with similar categories as for the analysis phase (Section 3.3).

3.5.1. Use of measured load segments (time histories or sequences)

With respect to the various loading and test conditions, synthesis of test load sequences by combination and repetition of measured loading segments is always possible. The main advantage of this approach is that all characteristics of the loading conditions are maintained with respect to the correct order, frequency contents, correlation functions or phase relations of load cycles. However, the resulting test sequence and time would be unacceptably long without further processing. Therefore, this approach has to be combined with time reduction methods which again depend on the loading and test conditions.

For uniaxial loading with stiff components (without environmental impact), the most effective time reduction is achieved by reduction of the load time histories to turning points and omission of small load cycles [56]. 'Allowable' filter levels for omission have to be defined with care, but the reader should refer to the literature with regard to this topic [56,57]. This type of approach was applied, for example, for the definition of the standardised fatigue loading sequences for helicopter rotors [62], in order to maintain fixed logical sequences of manoeuvres, Fig. 6. The additional inclusion of environmental exposure (e.g. temperature) may partly counterbalance the time reduction effect (comp. FALSTAFF and ENSTAFF).

The omission of low-intensity load segments (instead of single load cycles) is a less effective method that, nevertheless, has to be applied when real-time load histories need to be utilised, e.g. in case of dynamic response, connected with multiaxial loading. Also in case of investigations with automatic transmissions, real-time loading (torques and speeds) is required in order to trigger the automatic gear shifting operations properly [21].

For stiff components (negligible dynamic response), however, a reduction of testing time for multiaxial and/or rotating loading is also possible via the much more effective omission of individual load cycles if it is combined with an adaptation of the load–time history characteristics (load ramp rates) to the limits of the test facility. The procedure described in [22] computes optimised time-histories, taking into account the phase relations between 12 channels and the test facility limits in terms of frequency, velocity and acceleration. It was applied in [11,23].

3.5.2. Generation of load sequences by random drawing

In most standardisation applications, however, the more general (pseudo-) random generation procedures are preferred based on one or a set of load spectra that encompass the desired loading environment.

For the generation of a random sequence of *load cases* (realisation of the operating profile, Fig. 4), the *Markov* reconstruction is well suitable, because it takes into account successive events. It has been applied, e.g. for generation of the sequence of wind speed classes [24], sea states [12,13] and road types [10,23].

For synthesis of uniaxial random *load sequences* on a cycle-by-cycle basis, random drawing of load cycles from cumulative frequency distributions [58,60], Markov-reconstruction for stationary processes [59] up to the sophisticated rainflow reconstruction [10] have been used.

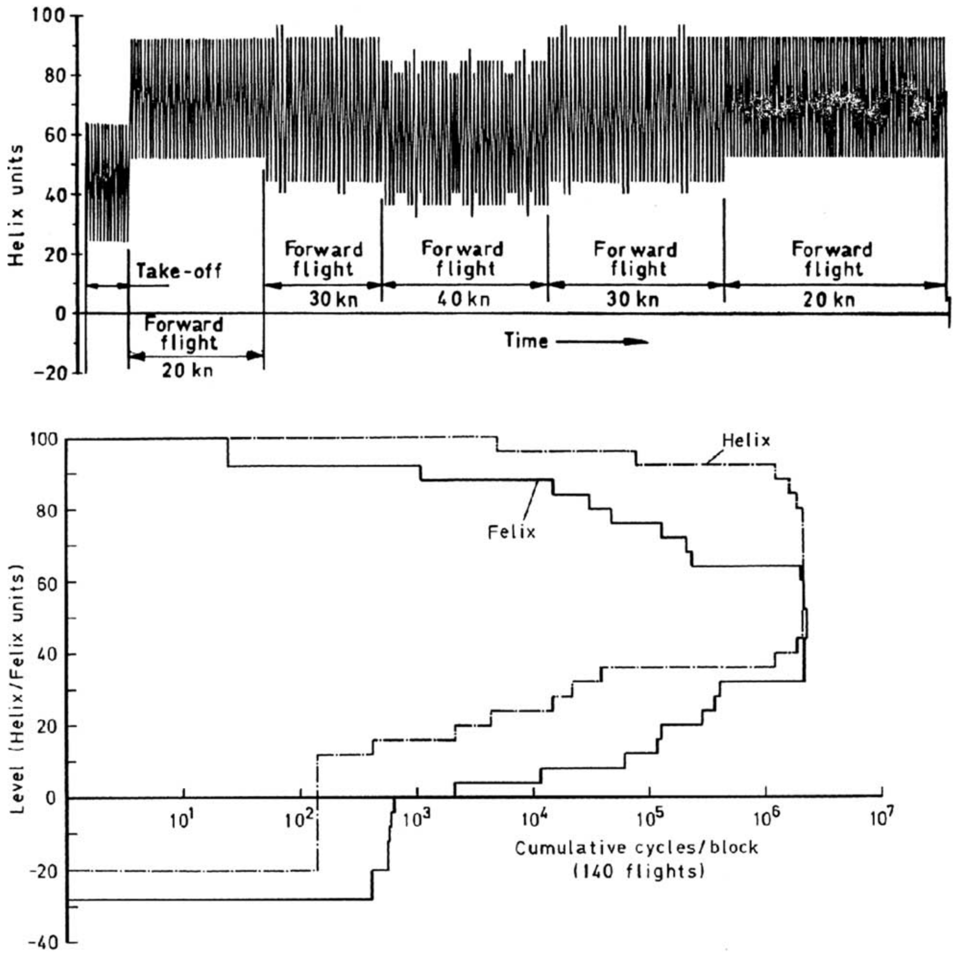

Fig. 6. Example of HELIX, first phase of a training flight (top) and level cross spectra of FELIX and HELIX (bottom).

For multiaxial loading combined with stiff test systems/components the so called *guide function procedure* is an appropriate concept that was applied in [23]. Guide functions are direct or processed elements (for example, weighted combinations) of load signals that are representative for specific loading causes such as cornering, accelerating/braking and the road condition (RMS-value of road roughness), Fig. 7. In the framework of this method, as a first step time histories of guide function values are generated under consideration of their respective joint density distributions. The resulting multi-directional and phase-related load vectors are then calculated from the guide functions (loading causes) in the time domain. The relationship between a given guide function level and the associated set of load vectors are provided by vehicle-specific transfer functions. This approach, Fig. 8 [23], was adopted for the development of CARLOS multi. In this application a stationary random process was generated and included as the (non-correlated) stationary part of road roughness loading in the guide function concept.

The Fourier procedures (like power spectral density) are particularly relevant for applications under dynamic test conditions. In this context it has to be emphasised that power spectra and other results of Fourier analyses are not directly fatigue-relevant, because load cycles are not clearly defined. For stationary Gaussian processes, however, a well-defined relation exists between power spectral densities and cumulative frequency distributions [19,25,26]. This means that the Fourier tools can be applied for stationary Gaussian processes even if they

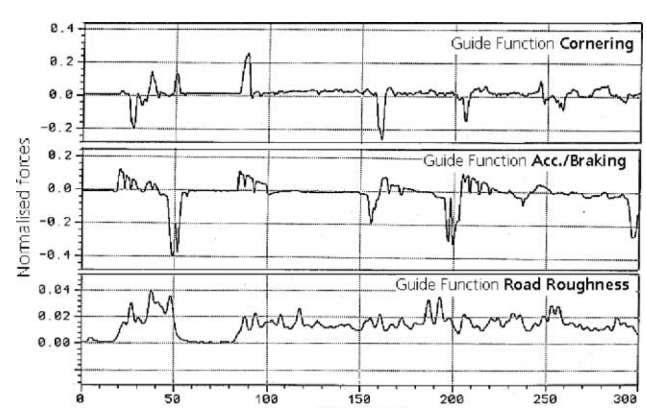

Fig. 7. Guide functions (CARLOS multi): e.g. cornering, sum of front lateral forces.

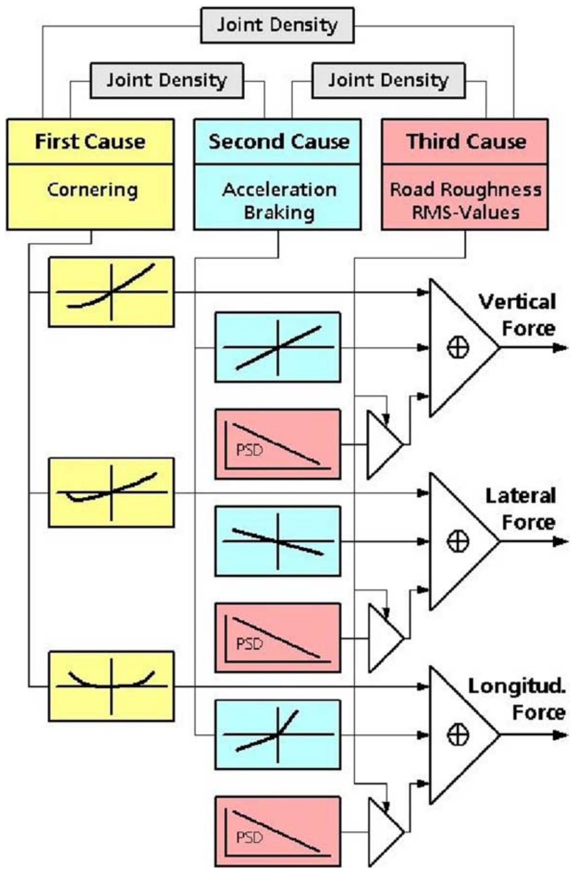

Fig. 8. Guide function approach for synthesis of partly correlated multiaxial load–time histories, car wheel suspension [23]; PSD, power spectral density.

are only a fraction of more complex load–time histories, as shown in Fig. 8.

4. Applications

4.1. Objectives of SLH's and general possibilities of application

After the introduction of servo-hydraulic test machines with closed control circuit at the end of the 1960s, it was possible to replace the constant amplitude and blocked program tests—applied exclusively before this time—by tests with near-service load sequences. However, besides the well-known advantages of these tests this led to an increase of test parameters and, consequently, to a loss of comparability. Yet, the comparison with already available results is very advantageous especially in case of fatigue tests. For this reason the first specific loading standards were created quite shortly after the introduction of the servo-hydraulic machines.

The use of loading standards is recommended for the following purposes:

- Evaluation of the fatigue strength of specimens or actual components made from different materials or by different manufacturing techniques;
- Optimisation of design details;
- Determination of allowable stresses for the preliminary fatigue design of components;
- Investigation of methods to increase fatigue life;
- Verification of models for the prediction of fatigue life and crack propagation;
- Investigations on the scatter of fatigue test lives;
- Round-robin programs on general fatigue and crack propagation problems with several participating laboratories;
- Basis for comparisons with current in-service measurements;
- Fatigue tests with prototypes as long as no design-specific load assumptions are available;
- New application-updating/amendment of directives of authorities.

Essential advantages of the application of service-like loading standards are:

- Availability at every stage of development;
- Reduction of the number of test parameters, comparability of results;
- Reliable (relative) fatigue estimates for current design and loading based on fatigue life curves determined under comparable loading conditions;
- Possible use as a main element of loading specifications for suppliers.

4.2. Applications

In the following, an overview is given on a number of examples from the literature where standardised load histories have been applied.

4.2.1. Round robins

The AGARD[2] conducted a number of round robins where a bulk of experimental data and numerical analyses were created with regard to cumulative damage problems. As an outcome of an AGARD conference on the short crack phenomenon [27], a large collaborative effort was initiated with participants from nine countries looking into test techniques and capabilities of numerical modelling of short crack growth under constant amplitude and spectrum loading. In a core programme [28] materials, test techniques and specimen geometries were agreed and the load sequence generation procedures of the FALSTAFF and Gaussian load histories were checked at the participating laboratories. In a supplemental programme [29] additional tests and crack growth predictions at short crack lengths were performed for all load spectra also including TWIST, MiniTWIST and HELIX. Materials considered were 2024-T3, 7075-T6, 2090-T8E41, Ti6Al4V and 4340 steel. In particular,

[2] AGARD (Advisory Group for Aerospace Research and Development), now RTO (NATO's Research and Technology Organisation).

crack-closure based models proved to successfully predict the fatigue lives; the knowledge (or assumption) of an initial crack size, however, appeared to be a critical issue.

Similarly another AGARD collaborative programme on engine disc materials was divided into two stages; in the core programme [30] test procedures and base-line constant amplitude data of smooth, notched and cracked Ti6Al4V specimens were determined. Thirteen participating laboratories from eight countries subsequently tested also coarser grained titanium alloys such as IMI 685 and Ti-17 [31]. Constant amplitude and overload tests were added to the variable amplitude tests using the original Cold TURBISTAN sequence as well as shortened sequences with three different omission levels. State-of-the-art crack growth models were applied. It was shown that for these particular load sequences non-linear effects were limited, but it was essential to adequately incorporate the effect of the R ratios ($R=S_{min}/S_{max}$) of the various load cycles involved.

A large AGARD co-ordinated programme [32,33] concentrated on the evaluation of corrosion fatigue behaviour of various aluminium alloys including 2024-T3, 7075-T6, 7010-T7451, 7010-T7461 and 7475-T761 under constant amplitude and spectrum loading (FALSTAFF, MiniTWIST). Owing to the increased complexity of the subject, the large test matrix considered a range of specimen types (smooth, notched, riveted joints) and test conditions (ambient, 3.5% NaCl solution, pre-corrosion, pre-damaging of protective systems applying high loads at −50 °C), etc. Pre-corrosion was found to be more detrimental for smooth and notched specimens, but there were also unexpected findings which indicated a higher reduction of corrosion fatigue lives at high load levels although the time the specimens spent in the corrosive medium was quite short at these high load levels.

As an outcome of the development of the TURBISTAN sequences, an international group with six participants from three countries was formed in 1989 to look into life prediction procedures for critical aero-engine components. Low cycle fatigue and crack growth related concepts were studied under relevant load conditions including constant amplitude tests, dwell tests and spectrum loading tests involving the Cold and Hot TURBISTAN sequences [34–36]. Smooth, notched and cracked specimens as well as model discs were machined from IN718 forgings that simulated present disc forging routines and tested in the cycle-dependent (400 °C) and mixed cycle-time-dependent (600 °C) regime. The test results highlighted the fatigue crack initiation and growth to be controlled by a complex interaction of material behaviour, stress state and load parameters further influenced by environmentally enhanced dwell crack growth at the higher temperature level. In the cycle-dependent regime the life prediction models worked quite well, but for the higher temperature level a need for more advanced modelling became obvious in order to provide robust predictive tools. As an interesting trend, quite low 'damage' contributions of small load cycles have

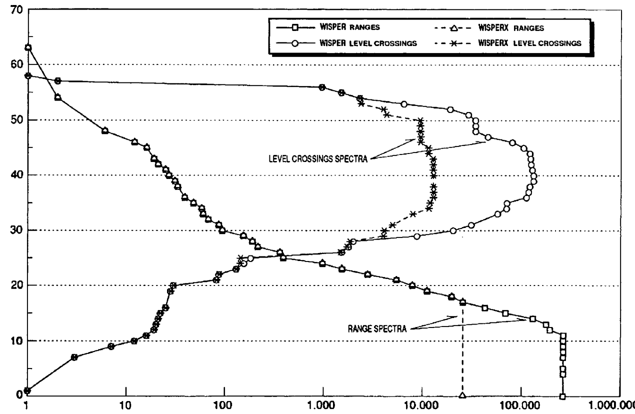

Fig. 9. Level crossing and rainflow (ranges) spectra of WISPER.

been determined which would enable potential savings for the life management of aero-engine hardware.

Other examples of this—inevitably in-complete—list could be mentioned such as studies on numerical life prediction procedures for components of helicopters (HELIX, FELIX) [37], vehicles (CARLOS) [38,39] and wind turbines (WISPER) [40,41,45]. CARLOS has also been used to investigate the fatigue behaviour of rubber parts [42,43] including the topic of allowable omission levels.

4.2.2. Generation of tailored load spectra and load sequences

Standardised load sequences carry the typical features of the load environments of a certain class of structures, vehicles, etc. Thus, they may not be appropriate or *directly* applicable to specific cases. Nevertheless, they may be used to support the generation of load spectra designed for specific applications.

WISPER/WISPERX [24] are wind turbine reference load spectra representative for a 2-month period based on data collected at northern European sites of rather smooth terrain often near the ocean, Fig. 9. The development protocol of WISPER was utilised to analyse load data of two wind turbines of a 41-row wind park operated in complex terrain at San Gorgonio Pass, California, and to derive a load spectrum representative of turbines operating under these conditions [44]. As outlined in [24] the two primary sources of fatigue loads of wind turbines, i.e. the wind inflow characteristics (external load source) as well as the design and operation of the turbine itself (load reactions) were analysed by adopting eight modes or classes of wind speed, Table 6.

Table 6
Wind speed classes used for the definition of WISPER

Mode 1	2	3	4	5	6	7	8
		10-min average wind speed (m/s)					
Start-up	Shut-down	<9	9–11	11–13	13–15	15–17	≥17

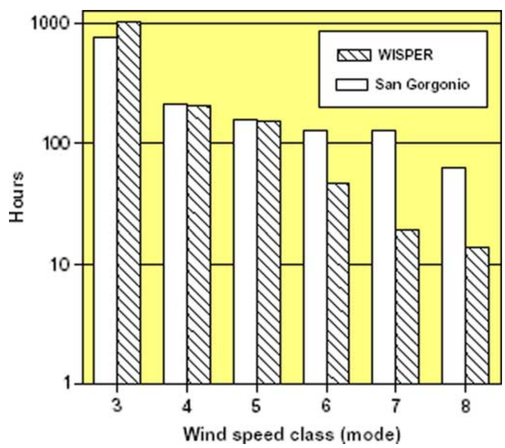

Fig. 10. Wind speed distributions according to WISPER and measurements at a Californian site [44].

The overall wind speed distribution which had been analysed by counting transitions into a 6×6 from-to Markov matrix showed a higher fraction of large wind speeds at the Californian wind park location, Fig. 10. The individual load cycles associated with each of the WISPER modes were rainflow-counted and normalised by the once-per-thousands revolution load levels, which enabled the evaluation of load data of wind turbines of rather different sizes as a common data base. The reconstitution of a final load spectrum was performed under consideration of the rainflow load ranges weighted by (a) the respective (average) load severities of the eight modes and (b) in proportion to the number of hours each mode (wind class) occurs in the overall wind inflow distribution, Fig. 11. The load spectrum of the San Gorgonio wind turbines was afterwards used within several studies e.g. [45].

Another example is described in [46] where the rotor head and the lift frame of rotorcraft were considered as part of a collaborative effort towards application of damage tolerance principles within the design and verification process of rotorcraft. The standardised sequences HELIX/FELIX represent loading on rotor blades, but it was judged appropriate to use relevant information pertinent to the definition of these sequences for the derivation of new load spectra for the points of interest. Therefore, the mix of helicopter missions and manoeuvres of HELIX/FELIX was used in combination with strain gauge data measured on two helicopters resulting in two new sequences named Asterix (lift frame location) [47] and Rotorix (rotorhead location) [48], respectively.

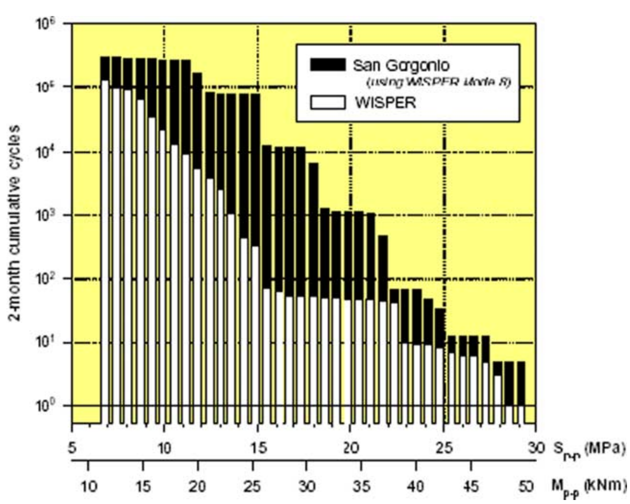

Fig. 11. Comparison of the WISPER spectrum and a 2-month spectrum derived on wind measurements and the WISPER protocol [44].

A further example is given by Broek et al. in a very illustrative report [49]. It is shown that the principles and various detail definitions of the TWIST sequence (typical for a *lower wing* location of transport aircraft), Fig. 12, can be used for and/or transferred to a new spectrum that may be applied to the fatigue and damage tolerance analysis of *fuselage* repairs (Fig. 12). It was argued that for the fuselage location, the large ground-air-ground cycle of the lower wing skin location corresponds to the cabin pressurisation cycle. This large cycle will be superimposed by load fluctuations which—under use of appropriate load-to-stress conversion factors—may be derived from the wing bending load patterns induced by gust and manoeuvre loading. Thus, many of the TWIST features such as the definitions of flights of different gust load severity, their relative cumulative frequency, the generation algorithms, etc. can be transferred to the new load sequence(s).

Along these lines, features of the TWIST generation principles have even been used for the definition of the full scale flight simulation test programme of the Fokker 100 aircraft as part of its fatigue and damage tolerance substantiation process as described in [50].

4.2.3. Using standardised load spectra as a reference

Often standardised load spectra may serve as a reference for individual load measurements or in-house definitions of test conditions.

In [51] the results of a measurement campaign on passenger cars are reported comparing the tire contact forces measured in Germany and Indonesia, respectively. Since the load characteristics clearly depend on the type and state of the roads (typical ranges of speed, manoeuvres and road roughness), the measurements were conducted under consideration of the classification outlined in the CARLOS load spectrum with the road types country road (good and bad), city road, highway, rough road. For an assessment of an overall load spectrum of the longitudinal, lateral and vertical forces, the operating profile of CARLOS, i.e. the relative fraction of these road types, was adopted as a European reference, which was contrasted to two different Indonesian profiles typical for usage in urban and remote environments, respectively. With respect to these particular measurements on German roads, the weighted load spectra of CARLOS turned out to be somewhat conservative, whereas Indonesian load intensities were higher by factors

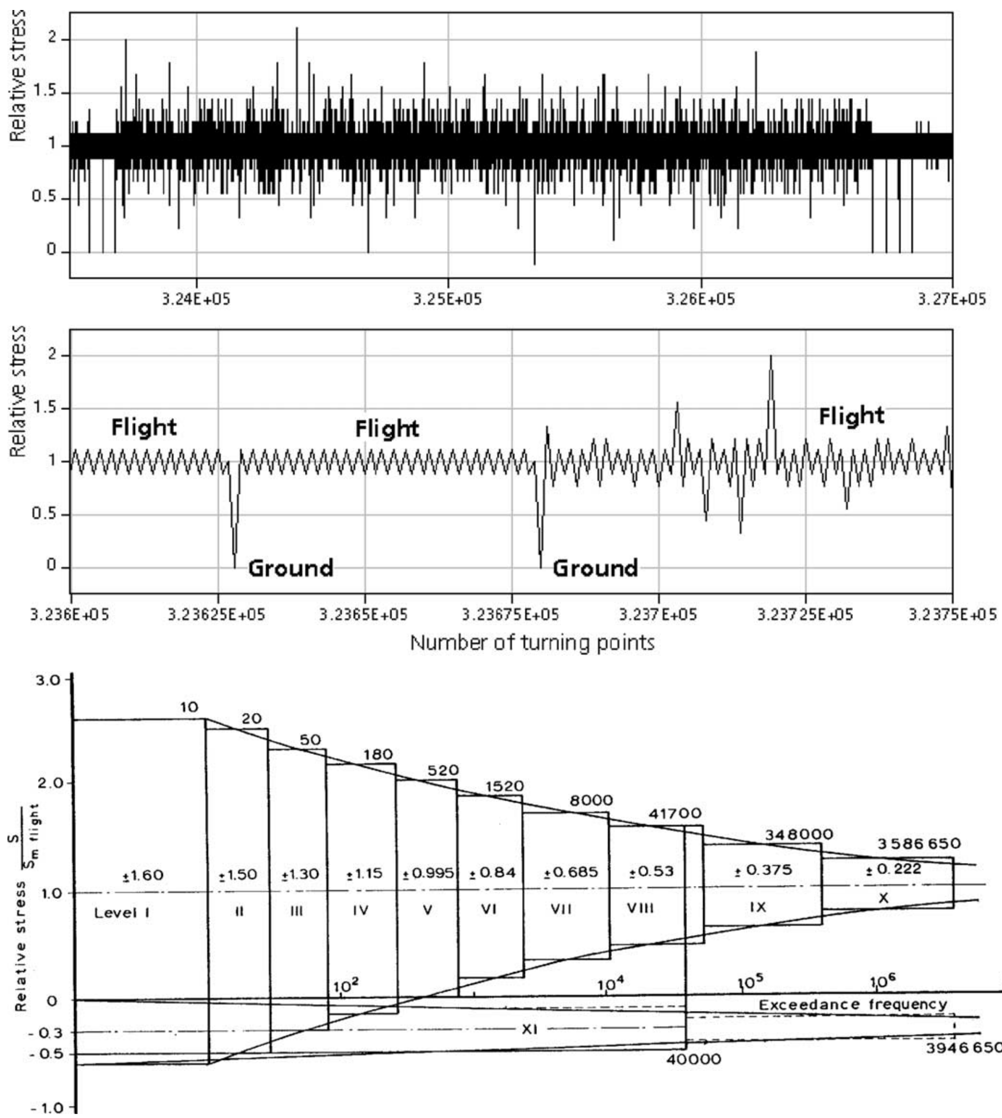

Fig. 12. Samples of the TWIST load sequence (top) and the TWIST spectrum (40,000 flights) consisting of gust, ground-air-ground and taxiing load elements (bottom).

between two and three compared to the 'damaging' contents of the respective CARLOS spectra.

The broad data base and the detailed analyses performed during the development of standardised load spectra often provide a more complete view that can be utilised to review ad hoc measurements or in-house procedures. During the development of the CARLOS spectra, the joint action of lateral, longitudinal and vertical forces were analysed and made available in the report. By comparison with respective data of a relevant in-house proving ground test track, one of the participants recognised that the test track produced the desired overall spectra of the individual force components, but failed to do so with regard to part of the joint actions of two or three forces, in other words, some of the manoeuvres that were identified for real customer usage were not reproduced on the test track. Based on the CARLOS analyses the test track could be optimised in order to meet the required joint distributions. In a similar case test protocols were adjusted by users based on the outcome of CARLOS Power Train where an overweight of low gear load intensities and an underweight of load intensities of higher gears was removed.

The WISPER load spectrum has been used to contrast the more severe wind load characteristics of turbines operating in complex terrain at continental sites [45]. These comparisons are based on load spectra directly measured as well as on WISPER and the wind park reference spectrum that has been derived by adopting the WISPER development protocol [44], see also Section 4.2.2. Comparison of load spectra is conducted mainly using Miner type life prediction data that may be interpreted as a weighted condensation of load spectrum content into a single number. Due to the nature of the reference load spectra considered the contributions of the external overall loading environment (long-term wind speed distributions) and the specifics of the design and operating conditions (smooth terrain single station vs. complex terrain wind park) to the final result could be separated and analysed. It was shown that the higher levels of turbulence prevailing at the wind park location produce high numbers of large load cycles for specific wind speed classes and therefore higher damage numbers. Besides it was noted that only a small percentage of high load ranges control the predicted damage numbers, which is particularly pronounced for the present case of fibreglass, laminates. This class of materials exhibit flat S–N curves with high slope exponents.

A similar approach was followed in [52] where long-term (37 days period) measurements were compared to the WISPERX reference spectrum using results of a life prediction exercise. In that particular case the results for both spectra were quite close together. Nevertheless the author stressed the case that WISPER/WISPERX have been developed not as tools for certification purposes and more long-term measurements are needed including also specific aspects like the potential influence of waves for wind turbines installed offshore.

5. Concluding remarks

The overview given in the paper shows that SLH's provide a useful base for a variety of fatigue-related issues. This is true for studies of more generic nature as well as for those looking into application problems. The more recent developments, in particular the CARLOS activities, are oriented towards real components and structures which certainly make them attractive for real-life qualification purposes. Qualification requirements imposed by OEM's to suppliers place a heavy burden to those companies, the more so when quite different test scenarios have to be adopted for different customers for a similar part. Here extended SLH's accepted by many OEM's (maybe with different design margins) would be advantageous and economic. The joint working group presently underway to establish advanced test scenarios for trailer coupling devices for passenger cars represents a good example. In the long-term, it may even establish the basis of a new test procedure released by European authorities that has to be followed as part of the qualification process of such equipment.

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